GLAST: UNDERSTANDING THE HIGH ENERGY GAMMA-RAY SKY

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Abstract

We discuss the ability of the GLAST Large Area Telescope (LAT) to identify, resolve, and study the high energy γ-ray sky. Compared to previous instruments the telescope will have greatly improved sensitivity and ability to localize γ-ray point sources. The ability to resolve the location and identity of EGRET unidentified sources is described. We summarize the current knowledge of the high energy γ-ray sky and discuss the astrophysics of known and some prospective classes of γ-ray emitters. Besides, we describe the potential of GLAST to resolve old puzzles and to discover new classes of sources.

Introduction

Our rudimentary understanding of the GeV γ-ray sky was greatly advanced with the launch of Energetic Gamma-Ray Experiment Telescope

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(EGRET) on the Compton Gamma-Ray Observatory (CGRO) in 1991. The number of previously known GeV γ-ray sources increased from 1–2 dozen to the 271 listed in the 3rd EGRET Catalog. The γ-ray sky was shown to be dominated by time-varying emitters. The science returns from these observations exceeded prelaunch expectations. Among them were the discoveries that for many blazars, intense γ-ray flares are seen, that many blazars and some pulsars have peak luminosity at GeV energies, and that the spectrum of GRBs extends to at least GeV energies. However, of this multitude of sources, only 101 have been definitively associated with known astrophysical objects. Thus, most of the γ-ray sky, as we currently understand it, consists of unidentified objects. This leaves intriguing puzzles for Gamma-ray Large Aperture Space Telescope (GLAST), the next generation GeV γ-ray instrument, to uncover.

One of the reasons that such a small fraction of the sources were identified is because the size of the typical γ-ray error box from EGRET was about 1 sq degree, an area that contains several candidate sources preventing a straightforward identification. Most of the identified GeV sources have distinct temporal features that allowed them to be associated with a known object. For example, the observation of pulsation allowed unambiguous association between radio pulsars and γ-ray sources, and the observation of correlated radio, optical or X-ray emission with γ-ray flares allowed the identification of several active galactic nuclei (AGN). This is why most of the high energy sources identified to date are either pulsars or AGN.

The large field of view and improved angular resolution of the LAT instrument on the GLAST mission will improve this situation dramatically. The angular resolution and "tails" on the point spread function are improved compared to EGRET so we will be able to refine maps of the γ-ray sky in crowded regions. The higher effective area allows flares from AGN and pulsations from pulsars and binary systems to be measured to correspondingly lower flux levels.

We begin with a brief description of the LAT as the next generation instrument in the GeV energy range. We will then discuss in Section 1.2 the questions raised by the EGRET results and the prospects for LAT studies of known and potential classes of γ-ray sources and speculate on their numbers. Useful and up to date information can be found in GLAST Science Brochure[1].

1. Instrument description

1.1 Hardware

GLAST is a major space mission to explore the high energy γ-ray universe. There are two instruments on board. The primary instrument is the GLAST Large Area Telescope (LAT), which is sensitive at energies from 20 MeV to 300 GeV. The secondary instrument is the GLAST Burst Monitor (GBM)[2] to detect γ-ray bursts and provide broad–band spectral coverage of this important phenomenon. The discussion of GBM is given elsewhere. Like EGRET, the LAT will detect γ-rays through conversion to electron-positron pairs and measurement of their direction in a tracker and their energy in a calorimeter. It uses a segmented plastic scintillator anti-coincidence system to provide rejection of the intense background of charged cosmic rays. A schematic of the LAT is shown in Fig. 1.

Along with increased area with respect to EGRET, the design of each element has been refined to improve the sensitivity and angular resolution and to extend the energy range to higher energy.

In the tracker, incident photons convert to electron-positron pairs in one of 16 layers of lead converter and are tracked by single-sided solid-state silicon strip detectors (SSD) through successive planes (the strips are centered every 228 microns). Tracking the pairs allows the reconstruction of the incident photon's arrival direction. The technology is the same as that used for precision measurements at the collision vertex in modern high-energy physics particle investigations. Multiple Coulomb scattering limits the angular resolution in the 30 to 300 MeV band, but the geometry of the SSD layers results in an important improvement over EGRET. At higher energies (>1 GeV) the precision of the EGRET spark chambers limited the ability of that instrument to take advantage of the intrinsic reduction in multiple scattering as energy increases. The very high measurement resolution of the SSD being used in the LAT means that the angular resolution is dominated by measurement uncertainty due to multiple scattering only above energies of 100 GeV. In determining source positions, each photon can be weighted in proportion to its energy, higher weight being given to higher energy particles whose arrival direction is better known. This results in an improvement in angular resolution that can reduce the source location error boxes by as much as a factor of 100 depending on the energy spectrum of photons detected and the local γ-ray background. Furthermore, LAT will have 10–20 microsecond deadtime to enable for far better efficiency for closely spaced (in time) γ-ray events during intense phases of γ-ray bursts and solar flares.

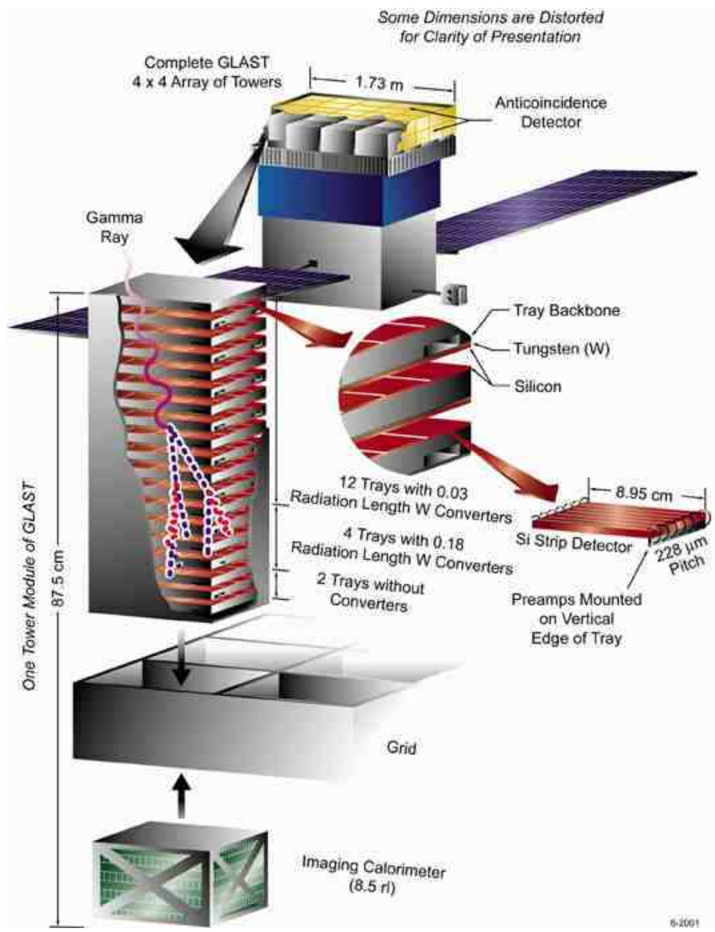

Figure 1. The GLAST Large Area Telescope.

A further subtlety in the LAT design can be found in the distribution of the thickness of the converter plates and SSD tracker planes. There are a total of 36 SSD planes, 18 (x, y)-pairs. The first 12 pairs (the front section of the tracker) are covered by tungsten plates, each of 0.03 radiation lengths (r.l.) thick, and the next 4 are covered by converters 0.18 r.l. thick, and the final 2 planes have no converter. In addition, there are about 0.405 r.l. in silicon detector and structural materials. The converter is thus 1.485 r.l. thick in total. The photons that convert in the front section (0.36 r.l.) give the highest angular resolution, while the back section assures that the overall photon detection efficiency is as

high as practical. The last two layers make sure we know the entry point of the particles into the calorimeter, where the tracking in the crystal layers, described below, continues.

The calorimeter consists of a segmented arrangement of 1536 CsI (Tl) crystals in 8 layers, giving both longitudinal and transverse information about the energy deposition pattern. This has several advantages over the shallower, monolithic calorimeter used in EGRET. The segmentation allows for the shower development in the calorimeter to be reconstructed resulting in a method of correction for energy leaking out the bottom of the calorimeter. Combined with the greater depth of the calorimeter this provides much the required energy resolution at high energies up to several hundred GeV. For normal incidence photons, shower maximum is contained up to 100 GeV. In addition, the segmentation allows the calorimeter to provide direction information of the γ-ray photon which can be used if the γ-ray photon did not convert in the tracker and provide important pattern recognition inputs for the rejection of background.

The AntiCoincidence Detector (ACD) provides most of the rejection of charged particle backgrounds. It consists of an array of 89 plastic scintillator tiles each with charged particle detection efficiency of 0.9997 read out by wave-shifting fibers and photomultiplier tubes. The segmentation prevents loss of effective area at high energy due to self-veto caused by low energy photons coming from the cascade showers in the calorimeter. This was an issue in EGRET that occured when albedo from showers in their calorimeter fired the monolithic ACD causing a 50% reduction in effective area at 10 GeV. The ACD is being designed so the LAT will have at least 80% efficiency for 300 GeV photons.

The GLAST mission will be flown in low-Earth orbit and will operate in both a "rocking" mode and a "stare" mode. In rocking mode the instrument moving 35 degrees north of zenith and then 35 degrees south about the orbit plane on alternate orbits. The instrument has a huge field of view; $\sim$20% of the sky at a time, and in rocking mode covers $\sim$75% of the sky every orbit. This is illustrated in Fig. 2 which shows the amount of sky coverage and sensitivity in Galactic coordinates for 3 different integration times while the instrument is in rocking mode. The top panel is for a 100 second observation. In rocking mode, the instrument does not move significantly during this time, so the extent of the non-black region indicates the size of the region of the sky that will be visible to the LAT at any instant. The middle panel shows the sensitivity after a one orbit (90 minute) observation. After two orbits (one with GLAST rocked north, and one rocked south) there is complete sky coverage. For a one day observation (bottom panel) the exposure on the sky becomes fairly uniform, the variations in point source sensitivity

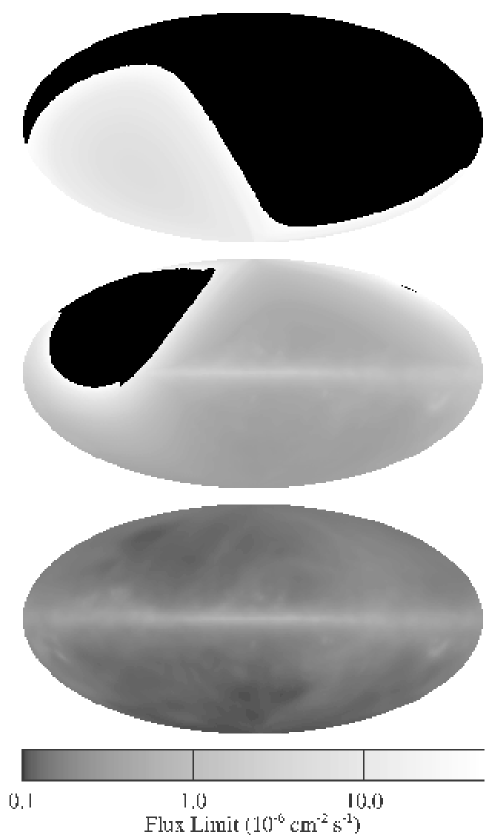

Figure 2 Sensitivity and sky coverage of GLAST (top to bottom) for 100 s, one orbit, and one day observations.

are dominated by the distribution of the background due to the Galactic diffuse emission. The sensitivity achieved after a single day observation is similar to the point source sensitivity of EGRET for the entire mission.

1.2 Instrument capabilities

The capabilities of GLAST's LAT are summarized in Table 1. The improvement in angular resolution will result in a much greater ability to localize sources. The area of source location error boxes will be reduced, compared to those of EGRET, by at least a factor of three depending on the source spectrum. This means that GLAST will be much more capable of resolving structure in the interstellar emission and separating point sources from extended or diffuse sources of emission. This will be of particular interest in, for example, locating and separating hot spots in supernova remnants from possible central point sources or resolving the positions of giant molecular clouds. Fig. 3 shows a simulation of the

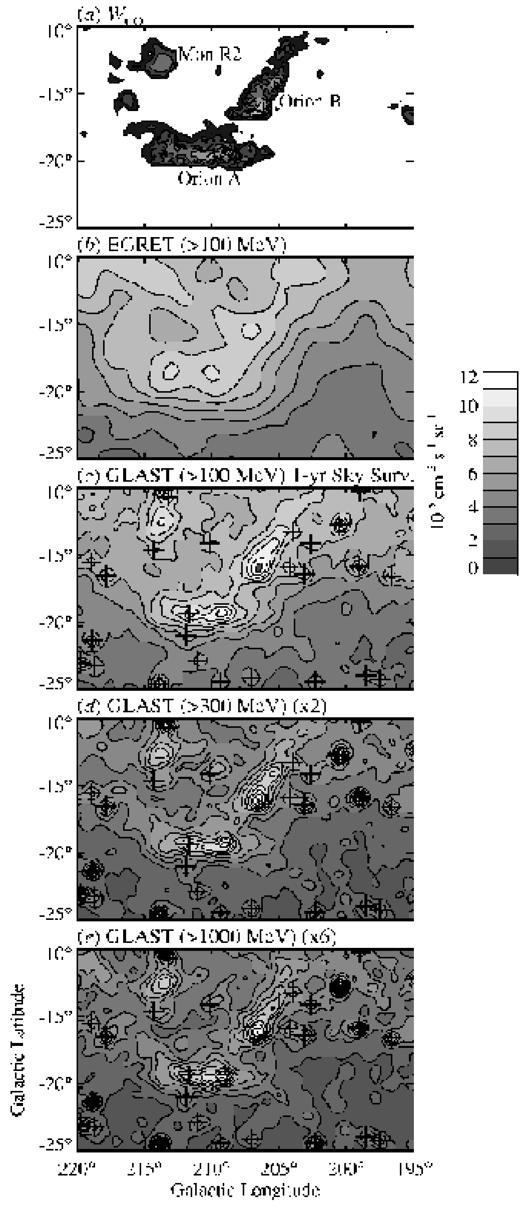

Figure 3 (a) Integrated intensity of the 2.6-mm CO line in Orion (Maddalena et al. 1986), showing the well-known Orion A and Orion B molecular clounds and the Mon R2 cloud. (b) Intensity of γ-rays with energies >100 MeV observed by EGRET and analyzed by Digel et al. (1999). (c-e) Simulated intensity maps from the GLAST sky survey for the energy ranges indicated. To smooth statistical fluctuations, the EGRET data were convolved with a Gaussian of FWHM 1.5°, and the GLAST intensities with FWHM 0.75°. Crosses mark the positions of background sources with fluxes greater than 10^{-8} cm^{-2} s^{-1} (>100 MeV). The intensity scale refers to (b-e) with scale factors as noted for (d-e) (Digel et al. 2001).

Orion region where point sources and extended diffuse emission may be intermingled.

GLAST will also fare far better in regions that were beset by problems of source confusion (where the sensitivity becomes limited by background due to unresolved sources) in the EGRET all-sky survey. Fig. 4 shows a

Table 1. Properties of the LAT compared to EGRET.

	EGRET	LAT
Energy range	20 MeV – 30 GeV	20 MeV – 300 GeV
Energy resolution	10%	9%
Effective area	1500 cm^2	10000 cm^2
Angular resolution	5.8° – 0.3°	3.4° – 0.09°
Field of view	0.5 sr	2.4 sr

comparison of the EGRET and simulated LAT response for the Cygnus region. This illustrates the dramatic improvement in source identification that will be possible with the superior source localization abilities of the LAT.

The increase in effective area will be of enormous importance for identification of sources via their temporal signatures. Flares from blazars will be detected at much lower flux levels and on far shorter time intervals. This greatly increases the likelihood of observing correlated variability in several wavebands, allowing a firm identification of the γ-ray source. The extra collection area will also be very important for pulsar observations. The only Galactic sources of high energy γ-rays that have been positively identified are all young rotation-powered pulsars, so it is likely that many of the unidentified sources are also pulsars. GLAST will be able to do blind periodicity searches on all EGRET unidentified

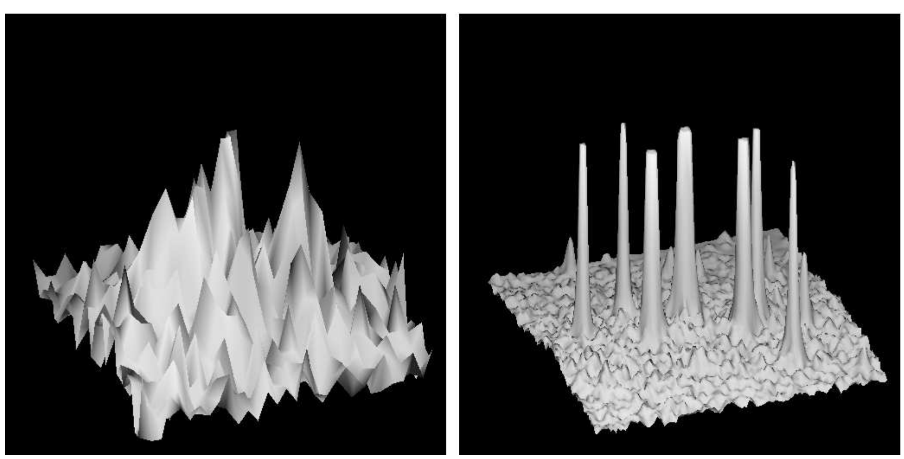

Figure 4. Cygnus region simulations (S. Digel, private communication).

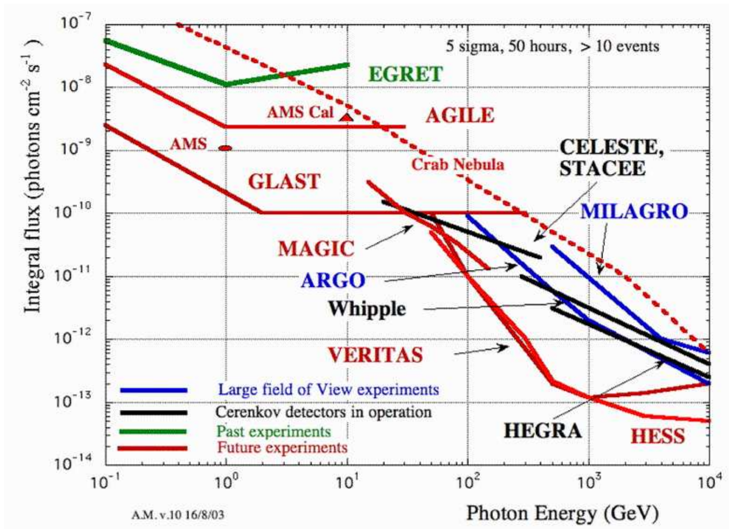

Figure 5. Sensitivities of past, current and future high energy γ-ray detectors (Morselli et al. 2000).

sources and thus determine which are pulsars. The LAT will have the potential to detect γ-ray variability from new classes of putative γ-ray bright objects such as Galactic microquasars or dim, decaying signals from γ-ray burst afterglows.

The extended energy range opens important new discovery potential for the LAT. The EGRET effective area fell off rapidly above a few GeV; the LAT has been carefully designed to maintain its area up to at least 300 GeV. This new high energy capability will provide significant overlap with the next generation ground-based γ-ray telescopes, as illustrated in Fig. 5. It shows the integral sensitivities of past, current and future high energy γ-ray instruments. This will provide complete spectral coverage from MeV to TeV energies for the first time. It covers the band over which we expect to see breaks in the spectra of extragalactic objects due to the $\gamma\gamma$-absorption on low energy photons in intergalactic space. At the same time, the calorimeter and its energy resolution capability allow searches for γ-ray lines or other spectral features in the energy band where the annihilation signatures of the dark-matter candidate particles might be found.

This combination of GLAST's operational capability of scanning and Earth avoidance and the LAT's increased field of view, effective area, angular resolution and extended energy range in combination yield a sensitivity about two orders of magnitude improvement in sensitivity compared to EGRET. This capability will be important to do population and broadband spectral studies of such sources as blazars, pulsars and gamma ray burst afterglows.

2. Prospects: known and potential γ-ray sources

There are only a few elementary processes capable of producing high energy γ-rays (see Chapter 2 for more details), but uncovering their relative efficiency provides us with important information about the physical conditions and reactions in distant places that can not be obtained by any other means. The intensity of the γ-ray emission via π^0-decay and bremsstrahlung depends on the target gas density, while the intensity of inverse Compton (IC) scattering depends on the density of photons. Measurements of the γ-ray flux from an object provides information such as the spectra and distributions of accelerated particles, magnetic and radiation fields and gas density and distribution. This information is vital for studies of most astrophysical environments.

The nucleonic γ-rays are generated through the decay of π^0-mesons produced in nucleus-nucleus interactions of accelerated particles with gas. Nucleonic γ-rays have a spectrum with maximum at approximately $m_\pi c^2/2 \approx 70$ MeV. For $E_\gamma \gg m_\pi c^2/2$ the spectral index resembles the index of the ambient energetic nucleons, α_p.

The leptonic γ-rays can be produced via bremsstrahlung and IC scattering of cosmic microwave background (CMB) photons, diffuse Galactic photons, and local radiation fields. Bremsstrahlung spectral index is approximately the same as lepton's in the whole range, α_e. The spectrum of high energy photons produced in IC scattering in the Thomson regime is flatter than the spectrum of electrons, $\alpha_\gamma = (\alpha_e + 1)/2$.

The LAT is particularly well suited for observations of γ-rays produced by bremsstrahlung, IC scattering, and π^0-decay since its energy range covers the regions where these processes play a major role. This orbital instrument together with a new generation of ground-based telescopes will measure the γ-ray fluxes and spectra with the high accuracy, required to provide insights into many different types of astrophysical objects, and thus decipher long-standing puzzles in cosmic-ray and γ-ray astrophysics.

This Section first describes the classes of known γ-ray sources and the major problems to be addressed by LAT, and then speculates on the LAT potential to discover the objects yet to be detected in γ-rays.

2.1 Galactic diffuse γ-ray emission

The diffuse continuum emission in the range 50 keV – 50 GeV has been systematically studied in the experiments OSSE, COMPTEL, EGRET on the CGRO as well as in earlier experiments, SAS 2 and COS B. A review of CGRO observations was presented by (Hunter et al. 1997). New models of the diffuse emission are being developed by the LAT team. A new model will be compared to the higher resolution data provided by the LAT and important scientific understanding, described below, will result.

The diffuse γ-ray emission is the dominant feature of the γ-ray sky. The diffuse continuum γ-rays are produced in energetic interactions of nucleons with gas via π^0 production, and by electrons via IC scattering and bremsstrahlung. In the plane of our Galaxy, the emissions are most intense at latitudes below 5° and within 30° of the Galactic center and along spiral arms. Each of the emission processes are dominant in a different energy range, and therefore the γ-ray spectrum, can provide information about the large-scale spectra of nucleonic and leptonic components of cosmic rays (see Fig. 6). In turn, an improved understanding of the role of cosmic rays is essential for the study of many topics in Galactic and extragalactic γ-ray astronomy. It is worth noting that an understanding of the spatial distribution and spectrum of the diffuse emission is also important for studies of discrete sources.

A self-consistent model of Galactic diffuse γ-ray emission should include cosmic-ray transport as the first step. Knowing the number density of primary nuclei from satellite and balloon observations, the production cross sections from the laboratory experiments, and the gas distribution from astronomical observations, one can calculate the production rate of secondary nuclei. The observed abundance of radioactive isotopes determines then the value of the diffusion coefficient, halo size and other global parameters (Strong and Moskalenko 1998).

The modeling of cosmic-ray diffusion in the Galaxy includes the solution of the transport equation with a given source distribution and boundary conditions for all cosmic-ray species. The transport equation describes diffusion, convection by the hypothetical Galactic wind, energy losses, and possible distributed acceleration (energy gain). Electrons lose energy due to ionization, Coulomb scattering, synchrotron emission, IC scattering, and bremsstrahlung. The study of transport

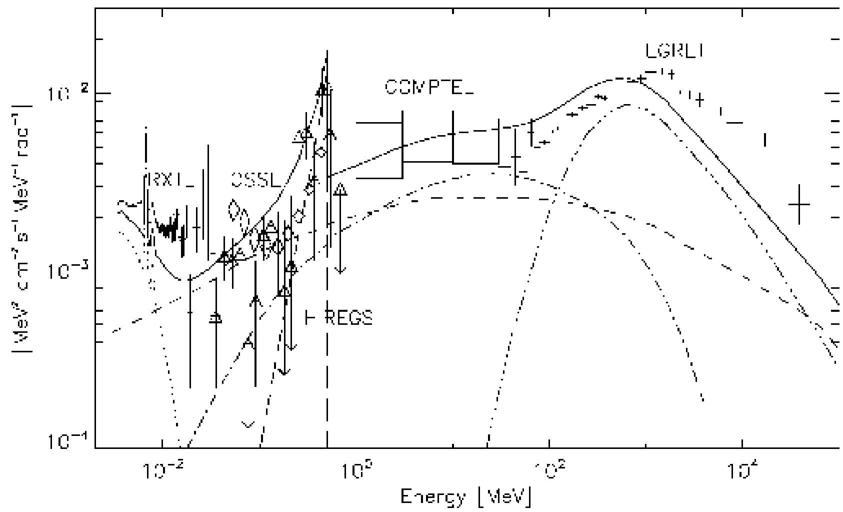

Figure 6. Multiwavelength spectrum of Galactic diffuse γ-ray emission. Hard X-ray/γ-ray Galactic diffuse emission as measured by HIREGS (triangles), RXTE, OSSE/CGRO (diamonds), COMPTEL/CGRO, and EGRET/CGRO. Also shown is the calculated flux (solid), and separate components: bremsstrahlung (dash-dot), IC (short dash), and neutral pions (triple dot-dash). Adapted from Boggs et al. (2000).

of cosmic-ray nuclear component requires consideration of nuclear spallation and ionization energy losses. The most sophisticated analytical methods include disk-halo diffusion, the dynamical halo Galactic wind, the turbulence and reacceleration (by second order Fermi acceleration and by encounters with interstellar shock waves).

The observation of diffuse γ-rays provide the most direct test of the proton and electron spectra on the large scale. The EGRET observations have confirmed the main features of the Galactic model derived from locally observed cosmic rays; however, they also brought new puzzles. The γ-rays revealed that the cosmic ray source distribution required to match the cosmic ray gradient in the Galaxy should be distinctly flatter (Strong and Mattox 1996) than the (poorly) known distribution of supernova remnants (Case and Bhattacharya 1998), the conventional sources of cosmic rays. The spectrum of γ-rays calculated under the assumption that the proton and electron spectra in the Galaxy resemble those measured locally reveals an excess at > 1 GeV in the EGRET spectrum (Hunter et al. 1997). This may indicate that the cosmic ray proton and/or electron spectra in the vicinity of the Sun are not representative of the Galactic average.

Since the γ-ray flux in any direction is the line of sight integral, attempts were made to explain the observed excess by a harder nucleon spectrum in the distant regions (Mori 1997; Gralewicz et al. 1997). However, it seems that the harder nucleon spectrum is inconsistent with other cosmic-ray measurements (Moskalenko et al. 1998) such as secondary antiprotons and positrons, which are also produced in *pp*-interactions. While the large deviations in the proton spectrum are less probable, the electron spectrum may fluctuate from place to place. The rate of energy loss for electrons increases with energy, it is thus natural to assume that the electron spectra are harder near the sources producing more high-energy γ-rays (Porter and Protheroe 1997; Pohl and Esposito 1998; Strong et al. 2000). IC scattering of Galactic plane and CMB photons off electrons provide a major contribution to the Galactic diffuse emission from mid- and high-latitudes. The effect of anisotropic scattering in the halo (Moskalenko and Strong 2000) increases the contribution of Galactic γ-rays and reduces the extragalactic component.

New measurements of the spectrum of diffuse continuum Galactic γ-rays by GLAST will address several long-standing problems. The large collection area and efficient operating mode will permit spectra to be derived for much smaller area bins than was possible with EGRET. This will allow for much better measurements of the latitude and longitude distributions of the diffuse emission allowing better constraints to be placed on its origin. The extension of the energy reach of the LAT will allow the excess above 1 GeV found by EGRET to be confirmed and characterized. This will greatly improve our understanding of the character of cosmic-ray diffusion and acceleration in our Galaxy and galaxies nearby. This in turn will allow the determination of a better background model for both point source and extended source studies.

More detailed discussion of Galactic diffuse emission may be found in Chapter 11.

2.2 Pulsars and plerions

Pulsars make up the second most numerous class of identified sources in the EGRET catalog which includes six confirmed and three candidate γ-ray pulsars (see Chapter 7 for more details). Many of the unidentified sources may be pulsars, however in many cases EGRET was not able to collect enough photons per source to perform independent period searches to detect these.

The lightcurves of all the EGRET pulsars show a double peak. Aside from the Crab the shapes of the radio and γ-ray profiles are often quite different with the peaks falling at different pulse phases. This implies

that low- and high-energy photons are most probably emitted from different regions and thus that their origin is different. Different mechanisms may be even responsible for emission of low- and high-energy γ-rays (McLaughlin and Cordes 2000), with the efficiency of converting the spin-down energy to high-energy γ-rays increasing with pulsar age. In the case of Geminga pulsar, one of the brightest γ-ray sources, most of its energy is emitted in GeV γ-rays (Jackson et al. 2002) while its radio emission has not yet been detected.

The spectra of these objects are very hard; pulsed emission above 5 GeV was seen by EGRET for all six confirmed γ-ray pulsars. However, spectral breaks are seen in most of these objects. PSR 1706–44 exhibits a break from a power-law spectrum with differential index of –1.27 to a power-law spectrum with index –2.25 above 1 GeV. Vela, Geminga, and the Crab all show evidence for a spectral break at around one GeV. Stringent upper limits on PSR 1951+32 and PSR 1055–52 at a few hundred GeV imply a spectral break for these objects (Srinivasan et al. 1997). However, there were insufficient detected photons to allow a determination of the shape of these spectral breaks. Searches for pulsed emission above a few hundred GeV by ground-based γ-ray detectors have so far only resulted in upper limits.

Two main types of models, polar cap and outer gap, have been proposed to explain the pulsar γ-ray emission (see Chapter 3 for more details). These have been succesful in explaining some features of γ-ray emission, but there is no model explaining all observations. The *polar cap* model (Daugherty and Harding 1996) explains the observed γ-rays in terms of curvative radiation or IC scattering of charged particles accelerated in rotation-induced electric fields near the poles of the pulsar. The superstrong magnetic field in the pulsar magnetosphere and the dense low-energy photon environment make it highly probable that high-energy γ-rays are converted into $e^{\pm}$-pairs. To escape, γ-ray photons should be directed outwards along the field lines. Another model, the *outer gap* model (Zhang and Cheng 1997), considers curvature γ-ray production by $e^{\pm}$-pairs in the regions close to the light cylinder. The pairs are created in $\gamma\gamma$-interactions of high-energy photons with thermal X-rays from the pulsar surface.

The high energy spectra of these two models are quite different, both predict a spectral break at high energies, but the phase resolved spectrum of the polar cap model falls off much more rapidly at high energies (super-exponential) compared to the outer gap model (exponential cutoff). There is also the possibility of a second, higher energy, pulsed component due to IC scattering expected in some outer gap models. Fig. 7 illustrates how the LAT high-energy response and spectral reso-

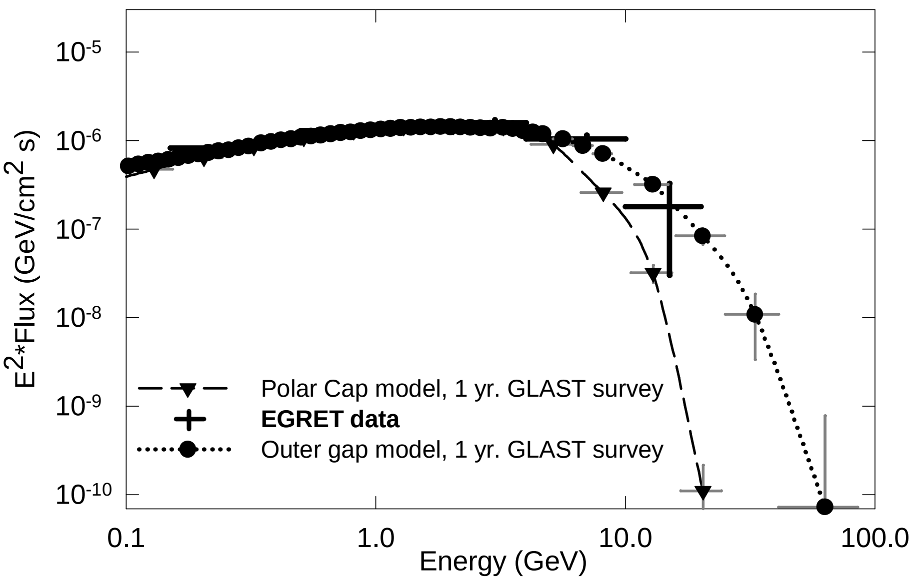

Figure 7. High energy spectrum of the Vela pulsar. Heavy error bars: EGRET data. Dotted line: outer gap model. Dashed line: polar cap model. Error bars shown on the models are those expected from the GLAST mission in a one-year sky survey (Thompson 2001, and references therein).

lution will enable these two models to be easily distinuished for bright pulsars.

The two types of models also predict different ratios of radio-loud and radio-quiet γ-ray pulsars. Polar cap models predict a much higher ratio of radio-loud to radio-quiet γ-ray pulsars, because in these models the high-energy and radio emission both originate in the same magnetic polar region. Thus a measurement of the ratio of radio-loud to radio-quiet γ-ray pulsars provides an important discrimination between emission models. GLAST will detect many more pulsars and thus will measure this ratio. The number of pulsars that GLAST will see depends on the emission mechanism and on the distribution of these sources on the sky. An empirical estimate made by extrapolating a $\log N - \log S$ curve of the known pulsars suggests that GLAST might expect to detect between 30 and 100 γ-ray pulsars. Fig. 8 shows one of the classic measures of pulsar observability, the spin-down energy seen at Earth. Six of the seven pulsars with the highest value of this parameter are γ-ray pulsars. The GLAST sensitivity will push the lower limit down substantially.

Understanding the physics of pulsar γ-ray emission may be important to determine the nature of the unidentified EGRET sources. 73 out of

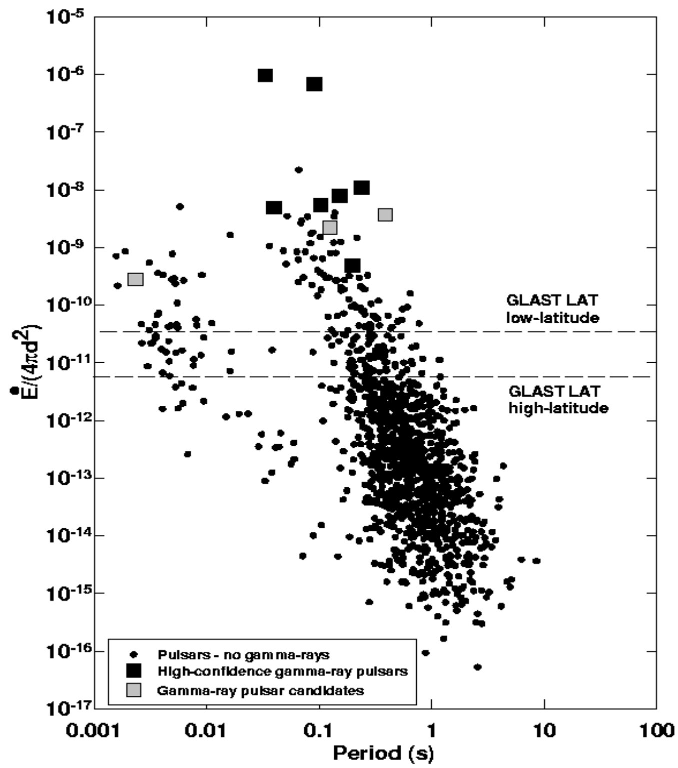

Figure 8. Gamma-ray pulsar observability as measured by the spin-down energy seen at Earth (Thompson, Chapter 7).

170 unidentified sources are located in or near the Galactic plane, and are likely to be pulsars or yet unknown source population. Some of them could be possibly associated with the Gould Belt, a massive star Galactic structure surrounding the sun. A new population of low-flux sources at an approximate distance 100–300 pc (Gehrels et al. 2000) may be misaligned young pulsars (Harding and Zhang 2001).

Observations with the LAT will improve our understanding of pulsars in several ways. The high-energy response and energy resolution will allow a determination of the shape of the high energy cutoffs in the bright pulsars. The increased collection area and thus improved photon statistics will allow a search for periodicities on timescales of millseconds to seconds in sources as faint as $\sim 5\times10^{-8}$ without prior knowledge from radio data, allowing for populations studies with these sources.

Studying the pulsar driven nebulae is another way to understand the physics of particle acceleration by pulsars. The Crab Nebula has been detected at TeV energies by several groups (Konopelko et al. 1998).

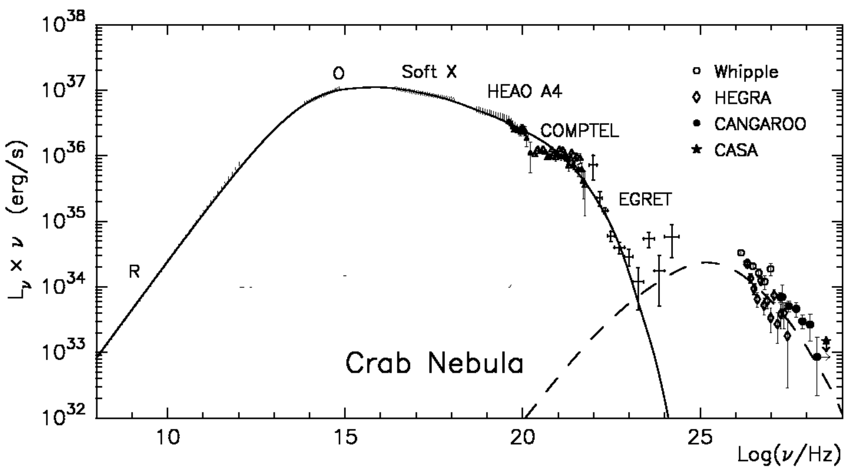

Figure 9. Multiwavelength spectrum of the Crab nebula. The lines represent a two component model; the solid line is synchrotron emission and the dashed line is IC emission. Adapted from Atoyan and Aharonian (1996).

There has also been reports of TeV emission from PSR 1706–44 (Kifune et al. 1995), and Vela (Yoshikoshi et al. 1997) by the CANGAROO collaboration.

The spectral energy distribution of the Crab Nebula, the best studied plerion, is shown in Fig. 9. There appear to be two components of the emission: synchrotron emission is believed to responsible for low-energy γ-rays down to radio, while IC scattering off CMB, dust far-IR, and synchrotron photons, is the most probable mechanism of high-energy γ-ray emission (Atoyan and Aharonian 1996). The energetic electrons responsible for this emission are provided by the pulsar wind or the wind termination shock. Another possibility which cannot yet be excluded is that some part of the γ-ray emission may be due to π^0-decay γ-rays.

Observations in the sub-TeV range will probe the emission mechanisms in plerions; allowing us to derive the nature of accelerated particles (leptons, hadrons), their spectra, and the intensity of the magnetic fields in the nebulae.

2.3 Blazars and radio galaxies

One of the surprises in AGN astrophysics over the past 10 years has been the detection of blazars at very high γ-ray energies. Most of the high latitude sources detected by EGRET were blazars, which are AGN

identified at other wavelengths to be either flat spectrum radio quasars (FSRQs) or BL Lacs. EGRET detected about 66 blazars of which 46 were FSRQs and 17 were BL Lacs (Hartman et al. 1999), at higher energies (>300 GeV) several BL Lacs have been detected by ground based γ-ray instruments (Punch et al. 1992; Quinn et al. 1996).

These objects are highly variable at all frequencies. High energy γ-ray flares have been observed on timescales of minutes to months. In fact, most of these AGN were only detectable by EGRET during γ-ray flares. Several multiwavelength campaigns have revealed that the γ-ray flares are frequently correlated with variability at longer wavelengths (Wehrle et al. 1998; Buckley et al. 1996). The γ-ray spectrum of blazars measured by EGRET is adequately fit by a simple power-law, although the data do not exclude more complicated shapes. The average spectral index in the EGRET energy band is about –2.2, with no evidence for a spectral cutoff for energies below 10 GeV (Mukherjee 1999).

The broadband spectral distributions are characterized by two components, one extending from radio to X-rays, interpreted as being due to synchrotron radiation, and another higher energy component. The origin of the high energy component is still a matter of considerable debate. Currently favored models include (a) electron IC scattering of synchrotron photons from within the jet or photons produced outside the jet, (b) proton initiated cascades, or (c) proton and muon synchrotron radiation. Simultaneous broadband observations of blazars, both in flaring and quiescent states, provide excellent tests of emission models (Buckley et al. 1996; von Montigny et al. 1995; Sikora et al. 2001).

In the most leptonic models, leptons accelerated by the central engine emit γ-rays via IC scattering of background photons (Katarzyński et al. 2001, and references therein). The background photons may be internal or external. Internal photons may be the synchrotron photons emitted by earlier generation of electrons (synchrotron-self-Compton models), while external can be CMB photons or photons reprocessed by a surrounding matter, e.g., gas clouds or the accretion torus (external IC models).

In the hadronic scenario, it is assumed that accelerated protons produce $e^{\pm}$ pairs in pp- or $p\gamma$-interactions. The pairs produce synchrotron or IC photons, which we see or, if the optical depth near the source is high, produce new pairs via $\gamma\gamma$ interactions and so on. To start the electron-photon cascade in this scenario there needs to be either a suitable gas target for accelerated nucleons, or the nucleons need to be accelerated to energies high enough to create pairs on background photons.

There may be systematic differences in several properties of blazars related to the location of the synchrotron peak, illustrated in Fig. 10.

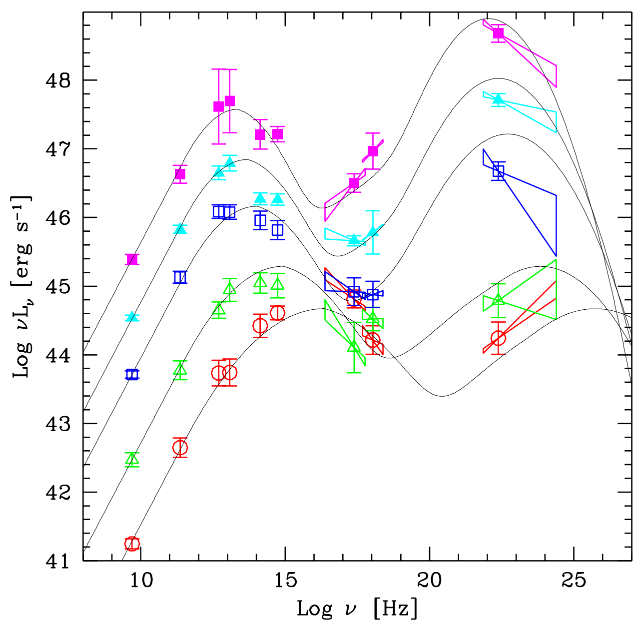

Figure 10. The points represent the average SEDs derived by (Fossati et al. 1998). BL Lacs and FSRQs belonging to complete samples have been divided into bins according only to the radio luminosity. The solid lines are the parameterisations of the spectra proposed in Donato et al. (2001).

As the synchrotron peak moves to lower frequencies; the ratio of the powers of the high to the low energy spectral components increases, the total power output of the blazar increases and emission lines become stronger, resulting in the sequence FSRQs, low-energy peaked BL Lacs and finally high-energy peaked BL Lacs. These differences have been interpreted as resulting from orientation (Ghisellini et al. 1989; Urry and Padovani 1995) or as intrinsic changes in physical parameters in the jet or jet environment (Padovani and Giommi 1995; Ghisellini et al. 1998). However, it is difficult to draw many conclusions about general properties of blazars from population studies at γ-ray energies. The sample of γ-ray blazars suffers from selection effects, GeV blazars were generally only seen during flares and only a few blazars have been detected at TeV energies. Some recent blazar surveys suggest that the apparent blazar sequence may be at least partially due to selection effects. Population studies by GLAST will help the study of blazars as a class by providing an unbiased set of data.

The peak sensitivity of the LAT lies at somewhat higher energies than that of EGRET. Thus it is likely that the LAT will identify an additional

population of blazars intermediate in properties between the EGRET detected and the TeV blazars. These are likely to include a much higher fraction of BL Lacs than were present in the EGRET sample. Studies of the high energy >10 GeV photons from blazars in the EGRET data suggest that they may be predominatly from BL Lacs, this work provides a taste of what might be still to come from GLAST. The actual number of blazars that will be detected by the LAT depends on the luminosity function and cosmological evolution of these objects, which, as yet, are unknown. Estimates of the number of blazars that will be detected by the LAT range from about 2500 to about 10000 objects. It is clear that the number of known γ-ray blazars will dramatically increase allowing for a much more detailed study of the underlying physical processes responsible for the blazar sequence.

The large field of view of the LAT will be of enormous importance for blazar observations. Most of the EGRET blazars were detected only when they flared. Since GLAST monitors (in the scanning mode) the entire sky on all timescales greater than an hour, all AGN anywhere in the sky that flare above the LAT detection threshold will be detected. This will likely lead to a dramatic increase in the number of known blazars and will require prompt follow up at many wavelengths to properly study and catagorise these sources.

Also of crucial importance is the ability of the LAT to generate detailed, complete lighcurves on all AGN in the sky on timescales down to hours. This will be a dramatic improvement over what was possible with EGRET. This is illustrated by Fig. 11 which shows the flux history of 4 blazars (Mukherjee 1999). The horizontal error bars indicate the duration of the observation. The limitations of these observations are immediately apparent. Flux variabilty can only be studied either on short timescales within an observation period, or on very long timescales with poor sampling between viewing periods. The large field of view of the LAT will allow continuous observations with increased sensitivity making possible studies on shorter timescales and of less intense flares.

Evidence for very high energy γ-ray emission has been reported for two radio galaxies. An EGRET source location is consistent with the location of Centaurus A (Sreekumar et al. 1999), the brightest AGN in the hard X-ray sky and one of the nearest. The HEGRA collaboration have reported emission from M87, another nearby radio-galaxy (Aharonian et al. 2003). Both M87 and Cen A are considered to be misaligned blazars, i.e. radio-galaxies aligned such that the relativistic jets are at large inclination angles to our line of sight (Morganti et al. 1992; Bicknell and Begelman 1996). Both of these detections are at somewhat marginal significance, and represent a significantly lower γ-ray flux than

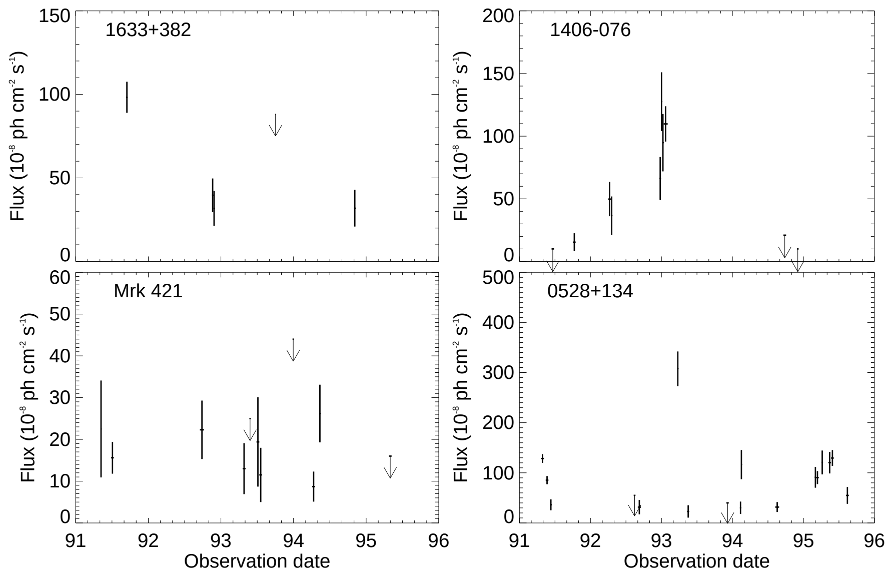

Figure 11. Flux history of 4 blazars (Mukherjee 1999): PKS 1633+382, PKS 1406–076, Mrk 421, and PKS 0528+134.

most blazars. However, these detections raise exciting possibilities with a more sensitive instrument like the LAT as the space density of radio galaxies are $\sim 10^3$ times that of blazars. Confirmation of γ-ray emission from radio galaxies and detection of a larger sample at a variety of inclination angles would provide valuable information about the parent population of blazars and the energy dependence of the beaming cones of blazars. Once the beaming cone is known, statistical studies can establish the paternity of BL Lacs and quasars to radio-loud Faranoff-Riley I and II galaxies (Urry and Padovani 1995).

2.4 Gamma-ray bursts

Gamma-ray bursts are extremely intense, but short-lived sources of γ-rays. Observations are generally made of two phases of a burst: the prompt phase, which is a short (milliseconds to thousands of seconds) period of very intense γ-ray emission and the afterglow phase which is observed at radio, optical, X-ray and γ-ray wavebands and decays on timescales of hours to days. High energy γ-ray observations of both phases are extremely important in understanding this extraordinary phenomenon.

EGRET detected four GRBs above 100 MeV, which were the brightest that occurred within the field of view of its spark chamber. EGRET also detected 30 GRBs above 1 MeV in its calorimeter. The high energy spectra are consistent with a power-law with no evidence for a cutoff below energies of 10 GeV. In one noteworthy burst, GRB 940217, EGRET detected high-energy emission persisting for about 5000 seconds beyond burst cessation at hard X-ray energies (Hurley et al. 1994); this high-energy γ-ray afterglow contained a significant fraction of the total burst fluence. A few other bright GRBs observed by EGRET also show indications of longer duration emission (Dingus, et al. 1997). A recent analysis of archival data from the EGRET calorimeter has found a multi-MeV spectral component in the prompt phase of GRB 941017, that is distinct from the lower energy component. This observation is difficult to explain within the standard synchrotron model thus indicating the existance of new phenomena (Gonzalez et al. 2003).

One of the most widely accepted models of the γ-ray burst phenomenon postulates that they are powered by a relativistically expanding fireball. Electrons accelerated at shocks produced by colliding shells of material inside the fireball (known as internal shocks) produce the radiation during the prompt phase via synchrotron emission. The afterglow is due to emission from non-thermal particles when the external shock formed when the fireball blastwave sweeps up the external medium. The high energy photons are (theoretically) the most difficult to produce and are easily lost due to conversion to e^+e^- pairs. They are thus of particular importance in constraining γ-ray burst physics.

There are several important questions about high energy emission from γ-ray bursts which remain to be answered. How high in energy does the emission extend? The measurement of the highest energy photons allows the determination of a constraint on the bulk Lorentz factor of the expansion. Pair production with lower energy photons will attenuate the high energy γ-rays unless the bulk Lorentz factor is large enough so that the γ-rays do not have sufficient energy to produce pairs in the rest frame of the fireball. It is important to establish whether there is, in general, a second higher energy component of emission in either the prompt or afterglow phases of a γ-ray burst, understanding the nature of such emission will provide important information about the physical conditions of the emission region (Zhang and Meszaros 1997; Pilla and Loeb 1998; Dermer and Chiang 2000).

One of the most important improvements of the LAT compared to EGRET is the very much reduced deadtime. The EGRET deadtime was about 110 ms per photon, which is comparable to the γ-ray pulse widths at lower energies where the time profiles are well measured. The

deadtime of the LAT will be <100 μs, so γ-ray burst observations will not be limited by the deadtime. This, combined with the large collection area, will allow the LAT to detect bursts to much lower intensities and to study the lightcurves on much finer structures than has previously been possible. The higher energy reach of the LAT will allow a systematic study of γ-ray bursts above 1 GeV. The LAT's field of view is more than four times that of EGRET which will result in many more bursts being detected. With some reasonable assumptions of the flux and spectral index distributions it has been predicted that the LAT will see >200 bursts per year.

2.5 Extragalactic diffuse emission

The extragalactic diffuse γ-ray emission is of particular interest as the bulk of these photons suffer little or no attenuation during the propagation from their site of origin. It is thus a superposition of all unresolved sources of high energy γ-ray emission in the Universe. The isotropic, presumably extragalactic component of the diffuse γ-ray flux was first discovered by the SAS-2 satellite and confirmed by EGRET (Thompson and Fichtel 1982; Sreekumar et al. 1998).

The spectrum of extragalactic diffuse γ-ray emission (EGB) is the most difficult component of the diffuse emission to extract. It depends strongly on the adopted model of the Galactic background which itself is not yet firmly established. It is not correct to assume that the isotropic component is entirely extragalactic, because even in the pole direction it is comparable to the Galactic contribution from IC scattering of photons from the Galactic plane and CMB photons off the halo electrons (Moskalenko and Strong 2000). The modelled emission depends on the size of the halo, the electron spectrum there, and the spectrum of low-energy background photons.

An extensive analysis has been undertaken (Sreekumar et al. 1998) to derive the spectrum of EGB based on EGRET data which is shown in Fig. 12. The distribution of modelled-Galactic-diffuse-emission along with the catalog of point sources were carefully subtracted from total-diffuse-emission to determine the EGB as an extrapolation to zero Galactic contribution. The spectral index that was obtained by this analysis, -2.10 ± 0.03, appears to be close to that of γ-ray blazars.

The origin of the isotropic background is uncertain, several possibilities have been proposed including barion-antibarion annihilation in the early Universe (Stecker et al. 1971), evaporation of primordial black holes (Page and Hawking 1976) and annihilation of exotic particles (Silk and Srednicki 1984; Rudaz and Stecker 1991) in addition to the contri-

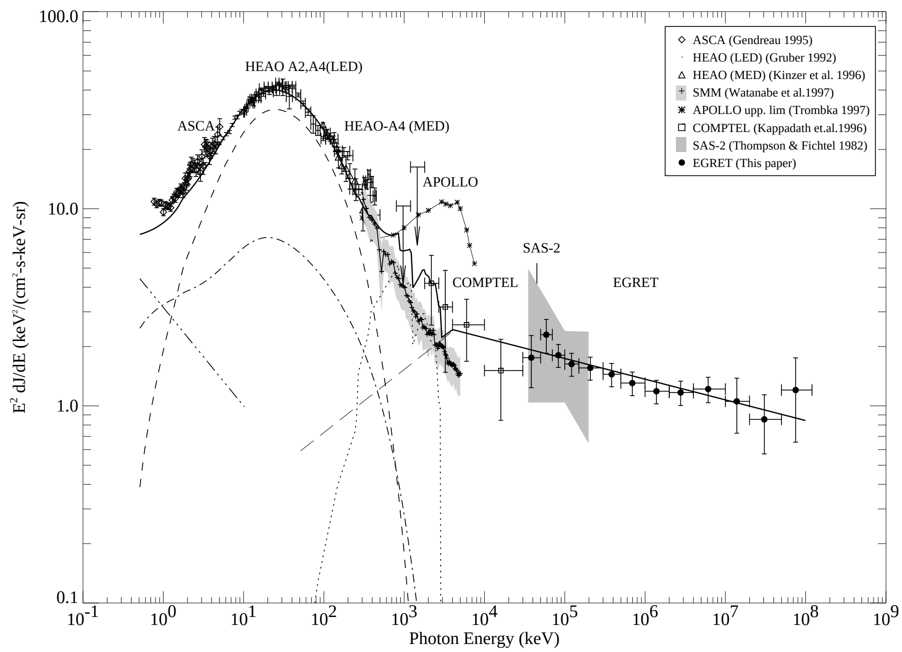

Figure 12. Multiwavelength spectrum of the diffuse extragalactic emission from X-rays to γ-rays taken from Sreekumar et al. (1998). The dot-dashed and dashed lines are estimates of the contributions of Seyfert I and Seyfert II galaxies respectively. The triple dot-dashed line represents the steep-spectrum quasar contribution and the dotted line is for type Ia supernovae. The long dashed line is an estimate of the contribution from blazars. The thick solid line is the sum of all components.

bution from unresolved extragalactic sources such as AGN, γ-ray bursts and galaxy clusters. Thus observations of the EGB can provide constraints on the existance of these phenomena and on their cosmological evolution.

Since most *identified* sources of extragalactic γ-rays are AGN, the *unresolved* AGN are likely to contribute to the EGB. There have been several analyses of the expected level of this contribution. Stecker and Salamon (1996) assumed that the γ-ray luminosity of blazars was proportional to their radio luminosity and used the measured radio luminosities to derive a luminosity function for γ-ray AGN; when integrated, this luminosity function indicates that unresolved blazars could contribute 100% of the extragalactic diffuse emission (Fig. 13). A direct determination of the blazar luminosity function from EGRET data leads to an estimate that the blazar contribution to the EGB is around 25% (Chiang and Mukherjee 1998). In a more recent analysis, the γ-ray luminosity

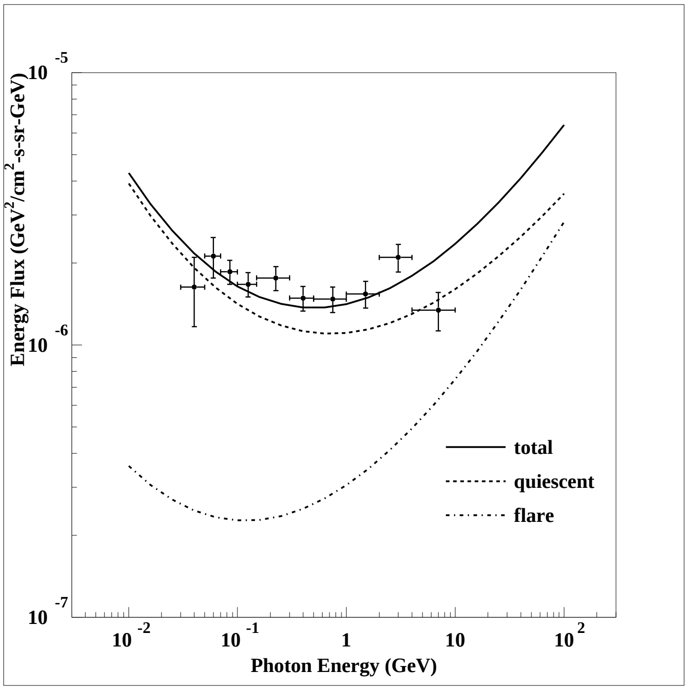

Figure 13. Predicted background spectra from unresolved blazars. The lower middle and upper curves show the contribution to the EGRB from flaring sources, from quiescent sources and their total (Stecker and Salamon 1996).

function (Mücke and Pohl 2000) is derived from a γ-ray emission model combined with an expected dependence of the AGN luminosity from orientation of the jet with respect to the line of sight. The results of this analysis suggest that between 20–40% of the EGB emission can be explained by unresolved AGN for an AGN luminosity function with a break at redshifts greater than 3 or even as much as 40–80% if the redshift cutoff occurs at $z = 5$.

Observations with the LAT will improve these limits in two ways: (i) studies of a larger population of AGN will allow the better determination of the blazar luminosity function and thus a more reliable estimation of the contribution from unresolved blazars, and (ii) the improved sensitivity and angular resolution means that many more AGN will be detected as resolved sources, thus lowering the residual isotropic background from unresolved sources. This is particularly interesting as it raises the exciting possibility of detecting the spectral signatures of a more speculative truly diffuse component. An example of such a spectral feature from the annihilation of relic neutralinos is shown in Fig. 14 (Ullio et al. 2002).

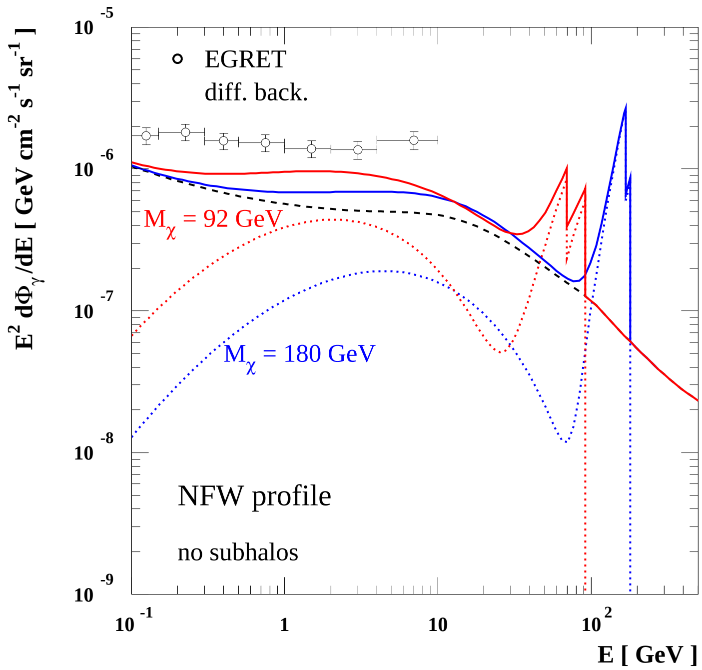

Figure 14. Extragalactic γ-ray flux (multiplied by E^2) for two sample thermal relic neutralinos (dotted curves), summed with the unresolved blazar background expected for GLAST (dashed curve) (Ullio et al. 2002).

2.6 Supernova remnants and cosmic-ray acceleration sites

One of the long-standing problems in astrophysics is the origin of cosmic rays. EGRET observations of the Small and Large Magellanic Clouds (Sreekumar et al. 1992) have shown that cosmic rays are likely to be Galactic in origin. Because of their energetics, supernova remnants (SNR) are thought to be the main sources of cosmic rays, at least, up to the "knee" in the cosmic-ray spectrum ($\sim 3 \times 10^{15}$ eV). Particles are believed to be accelerated by the shock waves of the SNR in the first-order Fermi diffusive acceleration mechanism, which should work for both leptons and nucleons. The resulting spectrum of accelerated particles is expected to approximate a power-law.

SNR can produce high-energy γ-rays of nucleonic and/or leptonic origin (see Fig. 15), however the spectral shapes of each are distinctly different (Gaisser et al. 1998). The bremsstrahlung spectrum is steep and thus dominates at lower energies, while the IC spectrum is flat and

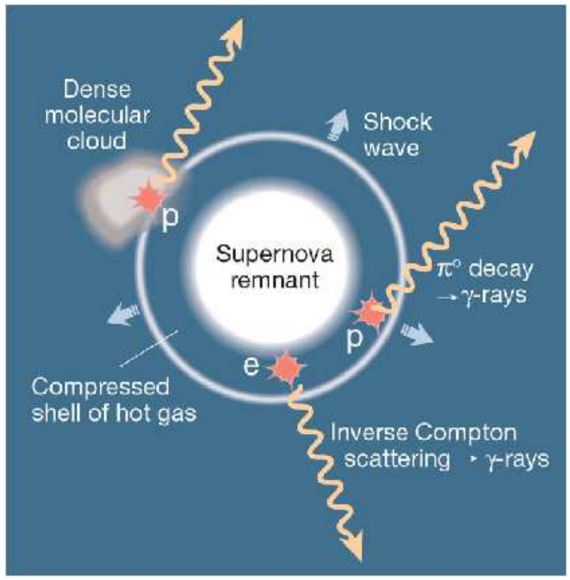

Figure 15. Shock waves from SNR can produce high-energy γ-rays in two ways: IC scattering of CMB photons off relativistic electrons, and π^0-decay from interactions of relativistic protons in the ISM. Adapted from Aharonian (2002).

contributes to higher energies. γ-rays resulting from π^0 decays display a bump in the spectrum which contributes to the intermediate energies (GeV-sub-TeV). This is a general picture, which may be not correct in details. Because of large energy losses of leptons via synchrotron and IC scattering the spectral index of accelerated leptons may be steeper than that of nucleons, thus the regions of dominance of different mechanisms can be, in reality, different.

Until recently, however, there was no direct evidence of particle acceleration in SNR. Strong non-thermal X-ray emission observed by ASCA from SN 1006 (Koyama et al. 1995), by ROSAT from RX J1713.7-3946 (Pfeffermann and Aschenbach 1996), by RXTE from Cas A (Allen et al. 1997), and several others have been interpreted as synchrotron emission of electrons accelerated up to $\sim$100 TeV. Detections of GeV γ-rays from the regions near several SNR have been reported by EGRET (Esposito et al. 1996). A number of unidentified EGRET sources have been statistically attributed to SNR (Sturner and Dermer 1995). Recent evidence of TeV emission from SN 1006 (Tanimori et al. 1998) and RX J1713.7-3946 (Muraishi et al. 2000) has been reported by the CANGAROO collaboration, and a detection of Cas A has been reported by the

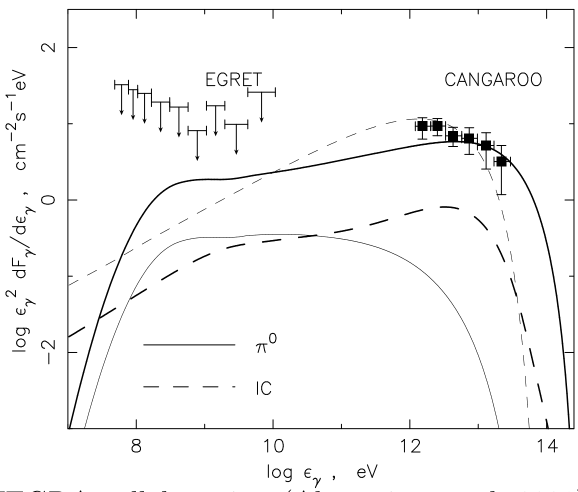

Figure 16 SN 1006. Differential π^0-decay (solid lines) and IC (dashed lines) for efficient (thick lines) and inefficient (thin lines) proton acceleration cases (Berezhko et al. 2002).

HEGRA collaboration (Aharonian et al. 2001). These detections represent the first *direct* evidence of particles, most likely leptons, up to $\sim$100 TeV. The observed TeV fluxes are consistent with being IC emission and the magnetic field of $\sim 10\mu$G can be derived from observations of the synchrotron emission.

While the high energy lepton population in remnants clearly manifests itself via synchrotron X-rays, acceleration of nucleons to high energies has yet to be observed. The estimated flux of γ-rays from π^0-decay at TeV energies is small; to detect it one needs an instrument capable of observations at sub-TeV energies with good angular resolution. There have been some arguments that the TeV γ-rays from SN 1006 (Berezhko et al. 2002), illustrated in Fig. 16, and RX J1713.7–3946 (Enomoto et al. 2002) in Fig. 17 are of hadronic origin, however the arguments and observations for this are not yet conclusive (Reimer and Pohl 2002; Butt et al. 2002).

Ultimate evidence of hadron acceleration would be π^0-decay γ-rays from a molecular cloud in the vicinity of a SNR (Aharonian et al. 1994; Aharonian and Atoyan 1996). An unidentified EGRET source 3EG J1714–3857 has been interpreted (Butt et al. 2001) as being a signature of π^0-decay γ-rays from nucleonic interactions in dense molecular clouds found in the vicinity of the TeV source RX J1713.7–3946. Another possible signature of π^0-decay γ-rays is the unidentified TeV source which has been found in the vicinity of Cygnus OB2 association (Aharonian et al. 2002).

The measurements of the γ-ray spectrum of a number of SNR by GLAST will help to solve several long-standing problems. The origin of cosmic-ray remains uncertain, the LAT should be able to address whether SNR are accelerating protons and, if so, to which energy. The

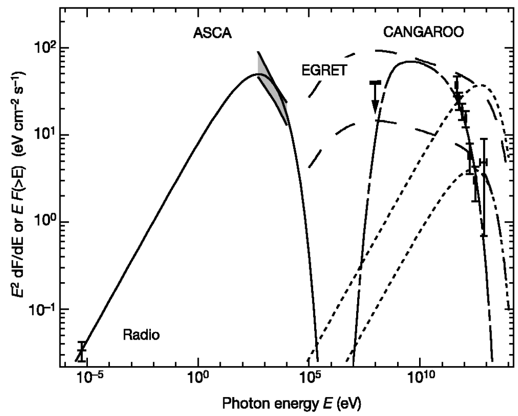

Figure 17 Multi-band emission from RX J1713.7–3946, and emission models. Model calculations: solid line – synchrotron emission, dotted lines – IC scattering, dashed lines – bremsstrahlung, short-long dahed line – π^0-decay. The IC and bremsstrahlung are shown for 3μG (upper curves), and 10μG (lower curves). Adapted from Enomoto et al. (2002).

LAT will also be able to study the energy output of SNR in high energy particles and probe electron/proton ratio of the accelerated particles. The understanding of the dominant mechanisms producing γ-rays in SNR will provide a wealth of information on the physical conditions near SNR, such as the gas density, the background photon field, and the magnetic field. The derivation of the spectra of accelerated particles will be very important in better understanding theories of shock acceleration. More detailed discussion of particular SNR and extensive references can be found in Chapter 5 and in Torres et al. (2002).

2.7 Galaxy clusters

Galaxy clusters have yet to be observed in γ-rays, but their significant content of nonthermal particles implies that their γ-ray emission should be detectable by the next generation of γ-ray telescopes. A signature of the presence of relativistic electrons in the intracluster medium is the detection of a diffuse cluster-scale radio emission from a number of these objects (Giovannini et al. 1999, and references therein). The intracluster magnetic field estimates range from 0.1μG to 1μG leaving a large window for speculations of the total energy content of relativistic electrons (and protons) there.

The non-thermal electrons in clusters are believed to be produced in several ways. Among the mechanisms discussed are the acceleration by merging shocks and injection of relativistic particles by active galaxies which may be members of the cluster. A significant fraction of nonthermal electrons can be produced by high energy protons in *pp*-interactions via production and decay of charged pions and from annihilation of supersymmetrical particles. Because of large energy losses electrons are

to be accelerated in a relatively short time scale of a few Byr, while high-energy protons can be accumulated on cosmological time scale.

Galaxy clusters are among the primary candidates to be associated with unidentified EGRET sources. Fifty out of 170 unidentified sources in the Third EGRET catalogue (Hartman et al. 1999) are found at intermediate and high Galactic latitudes, $|b| \geq 20^{\circ}$, and are likely to be extragalactic. The low flux variability of these sources implies that they can not be attributed to a highly variable AGN population. Spatial correlation with galaxy clusters and correlation between 1.4 GHz radio flux from the clusters and γ-ray flux supports this hypothesis (Colafrancesco 2002).

The γ-ray fluxes from electrons (bremsstrahlung, IC scattering) and protons (π^0-decay) have been predicted for some clusters using the radio, EUV, and X-ray observations. In the case of the Coma Cluster, EUV and X-ray observations show excesses compared to single-temperature plasma models (Fusco-Femiano et al. 1999; Rephaeli et al. 1999). If interpreted in terms of IC scattering of CMB photons by electrons of some 100 MeV (Ensslin and Biermann 1998; Sarazin and Lieu 1998), it yields the intracluster magnetic field of 0.1μG (Atoyan and Völk 2000) in contrast to $\sim 1\mu$G derived from Faraday rotation measurements. A magnetic field of $\sim 1\mu$G would produce synchrotron flux one order of magnitude higher than observed while falling short of explaining the EUV and X-ray fluxes due larger electron energy losses (Fig. 18).

GLAST sensivity will allow it to detect for the first time γ-rays from the galaxy clusters (Fig. 19). Such observations will help to derive the relative importance of γ-ray emission mechanisms and study physical conditions in the very-large-scale regions of the Universe. It would uncover mechanisms of particle acceleration in clusters.

3. Conclusions

One of the surprising results of observations above 100 MeV is the small number of classes of γ-ray sources (Table 2). At energies between 100 MeV and 30 GeV the only confirmed sources are pulsars/plerions, blazars, GRB, the sun and the Large Magellanic Cloud. In addition, based on spectral arguments, the nearby radio galaxy Cen A is believed to be associated with one of the sources in the EGRET 3rd catalog. At energies above 300 GeV the number of sources is very much smaller. At these energies several blazars and plerions have been detected by more than one instrument. In addition, there have been reported detections of a starburst galaxy, a radio galaxy, and SNR.

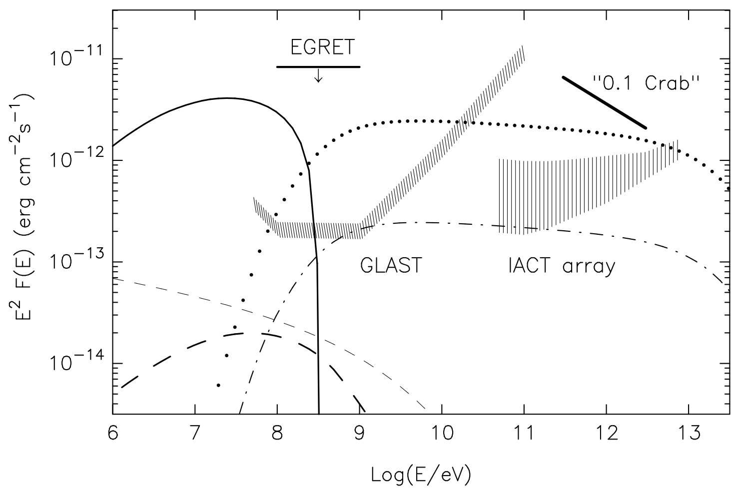

Figure 18. γ-ray flux expected from the Coma cluster. The solid curve shows the bremsstrahlung flux produced by the relic population of electrons (derived from the UV flux). Heavy dashed and thin dashed show the bremsstrahlung and IC fluxes produced by radio electrons ($B = 1\ \mu$G). Dotted and dash-dotted curves correspond to the π^0-decay produced by protons (index -2.1) with total energy 3×10^{62} and 3×10^{61} erg, correspondingly (Atoyan and Völk 2000).

One of the most unexpected features is the paucity of the overlap between these two catalogs. While blazars dominate the identified sources in both energy bands, the brightest TeV blazars are only weak GeV sources and the brighest GeV blazar is not detected at all at TeV energies. At GeV energies the pulsed emission from the Crab and Vela dominates, while at TeV energies only a DC excess from the plerion is observed. It is clear that the, as yet, unexplored region between 10 and 300 GeV will provide the key to linking together GeV and TeV γ-ray sky.

Table 2. Statistics of γ-ray sources at GeV and TeV energies.

	GeV	TeV
Pulsars/Plerions	6	3
SNR	0	2
AGN/Blazars	60?	6
AGN/Radio galaxies	1	1
Galaxies	1 (LMC)	1 (NGC 253)
GRB	4	0
Unidentified	170	1

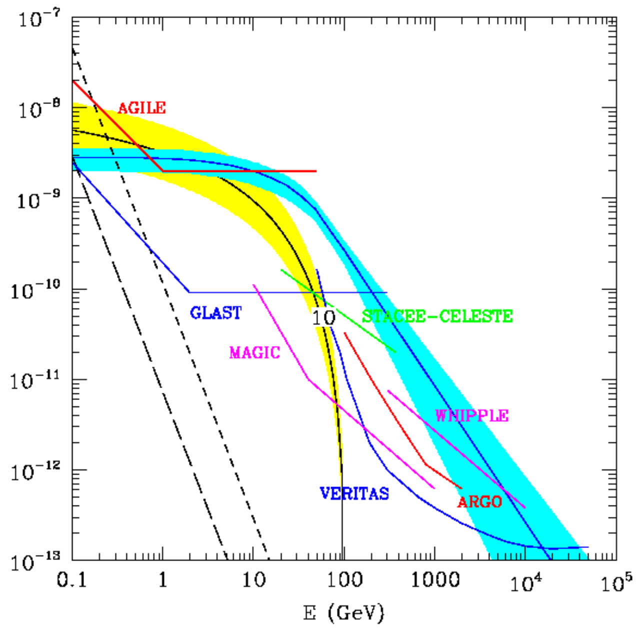

Figure 19. Coma cluster. Predictions for the γ-ray flux, $F_\gamma(> 100\text{MeV})$ cm^{-2} s^{-1}, expected for a Coma-like cluster are compared with the sensitivity of the next generation γ-ray experiments. Lines are coded as following: short-dash – electron bremsstrahlung for $B = 0.3$ μG, long-dash – electron bremsstrahlung for $B = 1$ μG, black curve – π^0-decay from pp-interactions and associated uncertainties (dark shaded region), black solid line – π^0-decay from neutralino annihilations and associated uncertainties (light shaded region) (Colafrancesco 2002).

With the launch of GLAST we will have the ability to explore at GeV energies many of the exciting questions raised by the EGRET observations. Foremost among these is understanding the nature of the many unidentified γ-ray sources. The LAT will have the ability to detect all of these sources with high significance and pinpoint the locations of these sources with sufficient accuracy that their identification may be relatively straightfoward. However, we note that this will not "solve" the issue of unidentified γ-ray sources. Thousands of new sources will be detected by the LAT. With a few exceptions, such as pulsars, identifing the nature of a γ-ray source can only be achieved by observations of these objects over a wide variety of wavebands. The better localization capabilities of the LAT will make multiwavelength observations easier (smaller field to survey) and thus more fruitful than was possible with EGRET sources. With the lowering of the GeV source sensitivity threshold of the LAT there will be a large increase in both the numbers and types of sources

detected at these energies, thus there will be a correspondingly increased importance in the role of multiwavelength observations to identify and study them.

New GLAST identifications will fall into 3 types: source classes already known to be γ-ray emitters, sources predicted to be γ-ray emitters and hopefully some complete surprises. We anticipate that observations of the GeV sky with the LAT will answer many of the intriging questions raised by EGRET and we look forward to discovering the new set of mysteries raised by the next generation instrument in this waveband.

Acknowledgments

The work by I. Moskalenko was supported in part by a NASA Astrophysics Theory Program grant.

Notes

1. GLAST Science Brochure: http://glast.gsfc.nasa.gov/public/resources/brochures/
2. GLAST Burst Monitor: http://gammaray.msfc.nasa.gov/gbm

References

Aharonian, F. A., and A. M. Atoyan, Astron. Astrophys., **309**, 917, 1996.

Aharonian, F. A., L. O'C. Drury, and H. J. Völk, Astron. Astrophys., **285**, 645, 1994.

Aharonian, F. et al., Astron. Astrophys., **370**, 112, 2001.

Aharonian, F. A.,Nature, **416**, 797, 2002.

Aharonian, F. et al., Astron. Astrophys., **393**, L37, 2002.

Aharonian, F. et al., Astron. Astrophys., **403**, L1, 2003.

Allen, G. E. et al., Astrophys. J., **487**, L97, 1997.

Atoyan, A. M., and F. A. Aharonian, Mon. Not. Royal Astron. Soc., **278**, 525, 1996.

Atoyan, A. M., and H. J. Völk, Astrophys. J., **535**, 45, 2000.

Berezhko, E. G., L. T. Ksenofontov, and H. J. Völk, Astron. Astrophys., **395**, 943, 2002.

Bicknell, G. V., and M. C. Begelman, Astrophys. J., **467**, 597, 1996.

Boggs, S. E. et al., Astrophys. J., **544**, 320, 2000.

Buckley, J. H. et al., Astrophys. J., **472**, L9, 1996.

Butt, Y. M. et al., Astrophys. J., **562**, L167, 2001.

Butt, Y. M. et al., Nature, **418**, 499, 2002.

Case, G. L., and D. Bhattacharya, Astrophys. J., **504**, 761, 1998.

Chiang, J., and R. Mukherjee, Astrophys. J., **496**, 752, 1998.

Colafrancesco, S., Astron. Astrophys., **396**, 31, 2002.

Daugherty, J. K., and A. K. Harding, Astrophys. J., **458**, 278, 1996.

Dermer, C .D., and J. Chiang, 2000, in *GeV to TeV Gamma-Ray Astrophysics Workshop: towards a major atmospheric Cherenkov detector VI*, eds. B. L. Dingus et al. (New York:AIP), AIP Conf. Proc., 515, 225.

Digel, S .W. et al., Astrophys. J., **520**, 196, 1999.

Digel, S .W., 2001, in *The Nature of Unidentified Galactic High-Energy Gamma-Ray Sources*, eds. A. Carramiñana et al. (Dordrecht: Kluwer), Astrophys. Space Sci. Lib., 267, 197.

Dingus, B .L., Catelli, J. R., and E. J. Schneid, in *Proc. 25th Int. Cosmic Ray Conf.* (Durban), **3**, 29, 1997.

Donato, D. et al., Astron. Astrophys., **375**, 739, 2001.

Enomoto, R., et al., Nature, **416**, 823, 2002.

Ensslin, T. A., and P. L. Biermann, Astron. Astrophys., **330**, 90, 1998.

Esposito et al., Astrophys. J., **461**, 820, 1996.

Fossati et al., Mon. Not. Royal Astron. Soc., **299**, 433, 1998.

Fusco-Femiano, R., et al., Astrophys. J., **513**, L21, 1999.

Gaisser, T. K., R. J. Protheroe, and T. Stanev, Astrophys. J., **492**, 219, 1998.

Gehrels, N. et al., Nature, **404**, 363, 2000.

Ghisellini, G. et al., Astrophys. J., **340**, 181, 1989.

Ghisellini, G. et al., Mon. Not. Royal Astron. Soc., **301**, 451, 1998.

Giovannini, G., M. Tordi, and L. Feretti, New Astron., **4**, 141, 1999.

Gonzalez, M. M. et al., Nature, **424**, 769, 2003.

Gralewicz, P. et al., Astron. Astrophys., **318**, 925, 1997.

Harding, A. K., and B. Zhang, Astrophys. J., **548**, L37, 2001.

Hartman, R. C. et al., Astrophys. J. Supplement, **123**, 79, 1999.

Hunter, S. D., et al., Astrophys. J., **481**, 205, 1997.

Hurley, K., et al., Nature, **372**, 652, 1997.

Jackson, M. S. et al., Astrophys. J., **578**, 935, 2002.

Katarzyński, K., H. Sol, and A. Kus, Astron. Astrophys., **367**, 809, 2001.

Kifune, T. et al., Astrophys. J., **438**, L91, 1995.

Konopelko, A. et al., 1998, in *Proc. 16th Europ. Cosmic Ray Symp.*, ed. J. Medina (Alcala: University de Alcala), 523.

Koyama, K. et al., Nature, **378**, 255, 1995.

Maddalena, R. J. et al., Astrophys. J., **303**, 375, 1989.

McLaughlin, M. A., and J. M. Cordes, Astrophys. J., **538**, 818, 2000.

Morganti, R. et al., Mon. Not. Royal Astron. Soc., **256**, 1P, 1992.

Mori, M., Astrophys. J., **478**, 225, 1997.

Morselli, A. et al., Nucl. Phys. B, **85**, 22, 2000.

Moskalenko, I. V., A. W. Strong, and O. Reimer, Astron. Astrophys., **338**, L75, 1998.

Moskalenko, I. V., and A. W. Strong, Astrophys. J., **528**, 357, 2000.

Mücke, A., and M. Pohl, Mon. Not. Royal Astron. Soc., **312**, 177, 2000.

Mukherjee, R., 1999, in *Observational Evidence for Black Holes in the Universe*, ed. S. K. Chakrabarti (Dordrecht: Kluwer), 215.

Muraishi, H. et al., Astron. Astrophys., **354**, L57, 2000.

Padovani, P., and P. Giommi, Astrophys. J., **444**, 567, 1995.

Page, D. N., and S. W. Hawking, Astrophys. J., **206**, 1, 1976.

Pfeffermann, E., and B. Aschenbach, 1996, in *Roentgenstrahlung from the Universe*, (Garching: MPE), MPE Report, 263, 267.

Pilla, R. P., and A. Loeb, Astrophys. J., **494**, 167, 1998.

Pohl, M., and J. A. Esposito, Astrophys. J., **507**, 327, 1998.

Porter, T. A., and R. J. Protheroe, J. Phys. G: Nucl. Part. Phys., **23**, 1765, 1997.

Punch, M. et al., Nature, **358**, 477, 1992.
Quinn, J. et al., Astrophys. J., **456**, L83, 1996.
Reimer, O., and M. Pohl, Astron. Astrophys., **390**, L43, 2002.
Rephaeli, Y., D. Gruber, and P. Blanco, Astrophys. J., **511**, L21, 1999.
Rudaz, S., and F. W. Stecker, Astrophys. J., **368**, 406, 1991.
Sarazin, C., and R. Lieu, Astrophys. J., **494**, 177, 1998.
Sikora, M. et al. Astrophys. J., **554**, 1, 2001.
Silk, J., and M. Srednicki, Phys. Rev. Lett., **53**, 624, 1984.
Sreekumar, P. et al., Astrophys. J., **400**, L67, 1992.
Sreekumar, P. et al., Astrophys. J., **494**, 523, 1998.
Sreekumar, P. et al., Astropart. Phys., **11**, 221, 1999.
Srinivasan, R. et al., Astrophys. J., **489**, 170, 1997.
Stecker, F. W., D. L. Morgan, and J. Bredekamp, Phys. Rev. Lett., **27**, 1469, 1971.
Stecker, F. W., and M. H. Salamon, Astrophys. J., **464**, 600, 1996.
Strong, A. W., and J. R. Mattox, Astron. Astrophys., **308**, L21, 1996.
Strong, A. W., and I. V. Moskalenko, Astrophys. J., **509**, 212, 1998.
Strong, A. W., I. V. Moskalenko, and O. Reimer, Astrophys. J., **537**, 763, 2000.
Sturner, S. J., and C. D. Dermer, Astron. Astrophys., **293**, L17, 1995.
Tanimori, T. et al., Astrophys. J., **497**, L25, 1998.
Thompson, D. J., and C. E. Fichtel, Astron. Astrophys., **109**, 352, 1982.
Thompson, D. J., 2001, in *High Energy Astronomy*, eds. F. A. Aharonian & H. J. Völk (New York: AIP), AIP Conf. Proc., 558, 103.
Torres, D. F. et al., Phys. Reports, **382**, 303, 2003.
Ullio, P., L. Bergström, J. Edsjö, and C. Lacey, Phys. Rev. D, **66**, #123502, 2002.
Urry, C. M., and P. Padovani, Pub. Astron. Soc. Pacific, **107**, 803, 1995.
von Montigny, C. et al., Astrophys. J., **440**, 525, 1995.
Wehrle, A. E. et al., Astrophys. J., **497**, 178, 1998.
Yoshikoshi, T. et al., Astrophys. J., **487**, L65, 1997.
Zhang, L., and K. S. Cheng, Astrophys. J., **487**, 370, 1997.
Zhang, B., and P. Meszaros, Astrophys. J., **559**, 110, 2001.